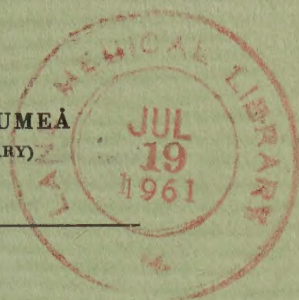


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THE PERCEPTION OF MUSCULAR WORK

A PSYCHOPHYSICAL STUDY OF SHORT-TIME WORK
ON THE BICYCLE ERGOMETER

By

GUNNAR BORG and HANS DAHLSTRÖM

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FROM THE DEPARTMENT OF CLINICAL PHYSIOLOGY AND THE
MEDICAL DEPARTMENT, THE MEDICAL SCHOOL, UMEÅ

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Standardized tests are often used when studying adaptation for physical work *e. g.* work on the bicycle ergometer, walking or running up steps or on a tread-mill, rowing in a rowing contrivance, turning the hand-wheel, lifting weights etc. It is then essential to express the working performance in measurable physical units, and to have a knowledge of the mechanical efficiency *i. e.* the external work in relation to the metabolic. Work on the bicycle ergometer seems to show that the mechanical efficiency is fairly constant for different persons. Consequently this and other practical advantages have resulted in the increased use of this particular working method.

A closer study of the connection between the perception of the work on the bicycle ergometer and the various physical parameters is of interest. A psychophysical study may later be followed by a psychophysiological investigation, whereby the various physiological parameters may be compared to the psychological. An increased knowledge of these spheres should also facilitate the study of the significance of factors concerning the psychology of personality in working tests.

Methods for measuring the intensity of perceptions have in recent years been launched by EKMAN (1958, 1959) and STEVENS (1951, 1957). For instance, the intensity of subjective brightness, subjective loudness, and subjective weight has been measured. Those scales of perception thus obtained are equidistant and have absolute zero points *i. e.* all mathematical operations are allowed.

The most important methods now available for the scaling of perception are the ratio setting, ratio rating, and magnitude estimation methods. In the ratio setting method the observer (*O*) must first experience

the standard stimulus, and is then instructed to change the intensity of a variable stimulus so that it is experienced as a part (method of fractionation) or as a multiple (method of multiple stimuli) of the standard. The set values, measured in physical units, of the O form the basis for the construction of the psychological scale. In the ratio rating method the O should attempt to estimate the relation between paired presented stimuli in per cent, and in the magnitude estimation method he should attempt to make direct numerical estimation of the subjective intensity of the presented stimuli. These methods of scaling appear to give similar results.

Those perceptive functions which belong to the so-called prothetic continua *i. e.* with an additive physiological process lying behind, all appear, according to STEVENS and GALANTER (1957), to be power functions. EKMAN (1959) suggests that these functions should be given the following general form: $R = c(S + a)^n$, where R is the intensity of the perception, S the intensity of the stimulus, c a constant related to the units of measurement used, and a and n constants which are determined experimentally, or $R = R_o + cS^n$, where R_o is "the basic perceptual noise, to which the subjective magnitude produced by external stimulation is added".

As regards work on the bicycle ergometer the following is generally applicable *viz.* that $P = \frac{W}{t}$ and $W = F \times v \times t$, where P is the power, W the work, F the force, v the pedalling speed, and t the time. The relation that exists between these physical parameters and the perception of work performed is unknown. Presumably this is not so simple. A series of relatively complicated inter-action effects of varying strength due to the power, time or speed chosen must be taken into account. Consideration must also be paid to a number of physiological parameters of varying importance to the type and intensity of the perception. By permitting the O to cycle for a short time the performance of work is limited to a relatively simple muscular dimension. The latter then probably belongs to the prothetic continua class, that is to say, the R - S -relation should even in this sphere be considered a power function of the type previously described. Hitherto no study has been made of those dimensions in which the perception of a muscular performance varies.

We are dealing with a general psychophysical problem. The aim in the first place is to relate the perceived muscular performance to the



FIG. 1. The bicycle ergometer.

physical parameters force, power and work. In subsequent investigations the aim will be to study closely the "intermediate" physiological parameters, and thereby be able to give an "explanation" of the *R-S*-function. An investigation of this type was conducted by STEVENS and VOLKMAN (1940). They compared the subjective pitch with the maximum of sensitivity along the basilar membrane.

A problem that seems to be unsolvable is the general validity of the subjective scale. At present there appears to be no possibility of determining any valid perceptive unit inter-individually. Another person's senses cannot be experienced, nor can the intensity of the perceptions of two people be immediately compared. Intrasubjectively valid scales and a mean curve with an arbitrarily chosen subjective unit may, however, be drawn up. It is possible that within the not too distant future a serviceable interindividual scale of perception will be realized with the aid of a series of physiological assessments of those parameters most essential to the perception.

Five series of experiments are reported in this paper to illustrate the possibility of applying modern psychophysical methods to the study of perceptions of performance on the bicycle ergometer. The investigation is limited to short-time muscular work.

Apparatus

A bicycle ergometer with an electric brake system was used (Fig. 1). The apparatus is constructed so that the physical power applied to the pedals is constant and independent of their revolutions per minute within certain limits. This is due to the electronic control of the pedaldriven generator. A speedometer gives the r.p.m. to enable the *O* to keep the speed constant. The *O* in our experiments had to maintain 60 r.p.m. The power desired is set by means of a graded resistor. The resistor knob can be given 10 turns from the one extreme position to the other. The handle bars of the bicycle ergometer were provided with a throttle handle of the motor cycle type which was connected to the knob of the resistor. The manipulation of the throttle necessitated the *O* to change his grip several times. It was thus impossible for the *O* to observe any adjusted power, nor did there seem to be any possibility of his ascertaining the number of turns of the handle.

Experiment I

The primary object of this experiment was to ascertain the possibility of measuring the intensity of perceived performance (perceived pedal resistance), when working on the bicycle ergometer, if individual variations exist and if the R - S -relation may be described with the aid of a power function of the type $R = c(S + a)^n$. Moreover, an attempt was made to determine the order of size of the constants a and n in this equation.

Method

The adjuster on the bicycle ergometer permitted the O to vary and set the comparative power continuously. It was, therefore, possible to work with the ratio setting method with halving. Power levels were chosen so that the O would perceive the lowest power as very easy, without being influenced by any zero effect when halving, and that the highest power would be perceived as very heavy. The intermediate power levels were chosen with equal distances between them: — 400 — 650 — 900 — 1,150 — 1,400 — 1,650 kpm/min. These 6 standard power levels were presented to the O according to a 6×6 Latin Square where the first row of standard power levels were chosen by lottery. When the O had become accustomed to the work on the bicycle ergometer and had experienced the whole scale of power he was instructed to feel, as thoroughly as possible, the pedal resistance and then to adjust the power so that the pedalling appeared to be half as strenuous. A pre-experimental training series was subsequently arranged for all the 6 levels.

With regard to previous bicycle ergometer tests and other short-time muscular experiments 30 seconds was considered a suitable time to work and perceive the standard. Then the O was allowed 15 seconds to perform the halving. Between each of the 36 assessments the O was allowed to rest 30 to 40 seconds by stepping off the ergometer and walking 10 metres. The whole experiment took about one hour. Four healthy male students of 22 to 25 years of age acted as O s.

Results

Table 1 gives the averages of each O 's half-values. Primary data have been reported by BORG and DAHLSTRÖM (1959). The averages of these half-values are given in Fig. 2 together with those for all the 4 O s' mean

values which are plotted against the respective S -values. As is seen in the Figure the values agree rather well with the straight lines; this means that the R - S -functions may be described as power functions. Seeing that the subjective halving line for the averages is above the physical, n is > 1 . The constants of the power functions a and n may be calculated algebraically according to the EKMANN method (1958). In Fig. 2 we proceed from the mean line: $S_{1/2} = b + kS$. In the equation $R = c(S + a)^n$ is $a = \frac{b}{k - 1}$ and $n = \frac{\log 0.5}{\log k}$. In this case the values of b and k may be assessed graphically from Fig. 2:

$$b = -35 \quad k = \frac{620 + 35}{1,000} = 0.655.$$

$$a = \frac{-35}{0.655 - 1} \approx 100 \quad n = \frac{\log 0.5}{\log 0.655} = 1.6$$

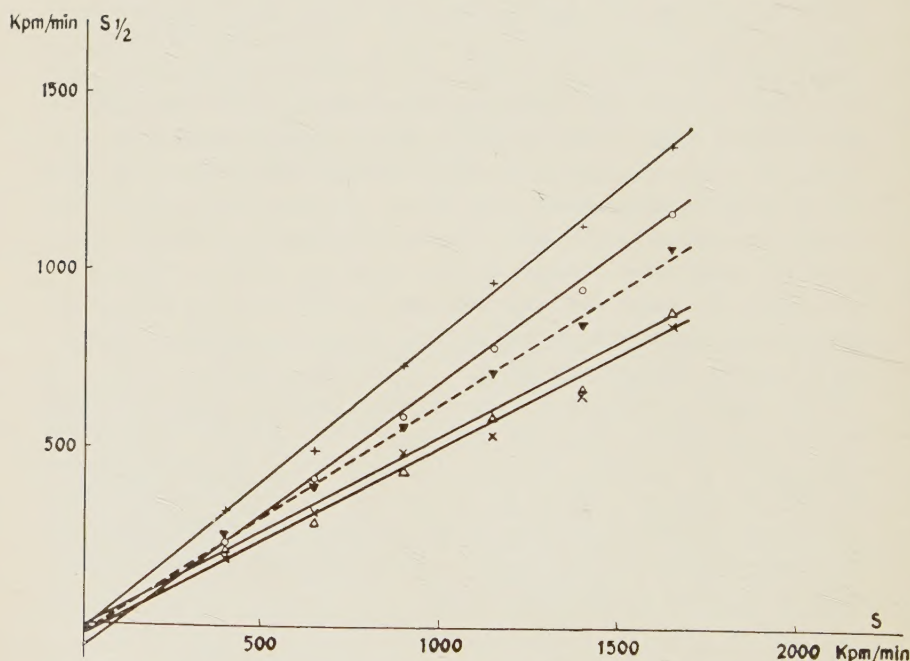


FIG. 2. Results of Experiment I. *Abscissa*: Stimulus values. *Ordinate*: Half-values. Each point represents mean values for 6 determinations. The broken line represents the mean values for the 4 subjects.

By including a and n in the above equation we get $R = c(S + 100)^{1.6}$. The curve for the R - S -function is given in Fig. 3.

To test the reliability of the differences between the O s a two-way analysis of variance was carried out. The estimated variance and the degrees of freedom are found in Table 2, for O i. e. individuals (i), power (p), interaction between O and power (ip) and within O (w). F_i and F_p , which were tested with s_{ip}^2 in the denominator are obviously highly significant. Thus this denotes a highly significant difference between our O s' half-values for various power levels.

The reliability is generally defined as the relation between true variance and total variance, or $r_u = 1 - \frac{\sigma_e^2}{\sigma_t^2}$ where σ_e^2 = the error variance and σ_t^2 = the total variance. With s_i^2 as the estimated total variance and s_{ip}^2 as the estimated error variance, $r_u = 0.95$.

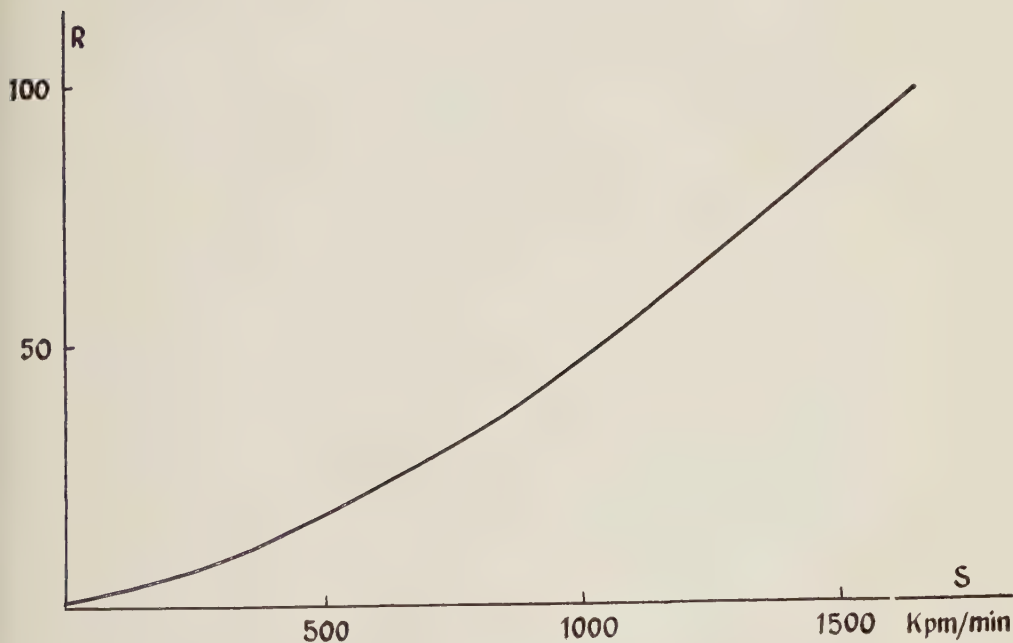


FIG. 3. Results of Experiment I. The R — S curve corresponding to the mean value line in Fig. 2 and the function $R = c(S + 100)^{1.6}$

Table 1. Experiment I. Half-values, $S_{1/2}$ for 6 standard power levels, S , and 4 Os. Averages of 6 values per O. in kpm/min

O	Power					
	400	650	900	1,150	1,400	1,650
1	237	418	591	786	950	1,166
2	322	493	731	965	1,123	1,353
3	190	316	491	540	655	851
4	214	295	429	584	667	881
Mean	241	380	560	719	849	1,063

Table 2. Experiment I. Two-way analysis of variance of half-values

Source	Sum of Squares	df	Variance Estimate
Individuals, i	2,635,096	3	878,365
Power levels, p	11,077,058	5	2,215,412
Interaction, ip	556,668	15	37,111
Within cell, w	688,817	120	5,740
Total	14,957,639	143	

$F_i = 23$; $F_p = 59$; $F_{ip} = 6.5$ (0.001 level at $F = 3.02$)

Experiment II

In this series of experiments the aim was to study the so-called "time-order error" *i. e.* the "memory error", which arises as a result of the order and the period of time between the perception and the reproduction. As regards halving experiments it is actually the memory of S and not S itself which is halved. An attempt was therefore made to ascertain if the O , when reproducing a standard power, set a power above, under or equal to this standard power.

Method

The experimental conditions were the same as in the previous experiment. As a standard power level 600 kpm/min was used and perceived for 30 seconds. Twelve women whose ages ranged from 20 to 30 were

the O_s . Reproduction of the standard power was carried out, in ascending series, when the technician for less than one second had changed the power to a lower level, and in descending series, when the technician had changed the power to a higher level, ten in each with a rotation according to the a b b a principle.

Results

The distribution of all the reproduction values (12×10) in ascending and descending series is given in Fig. 4. The averages for each O 's ascending and descending values are collocated in Table 3 together with the standard errors which were estimated from these 12 values. The average

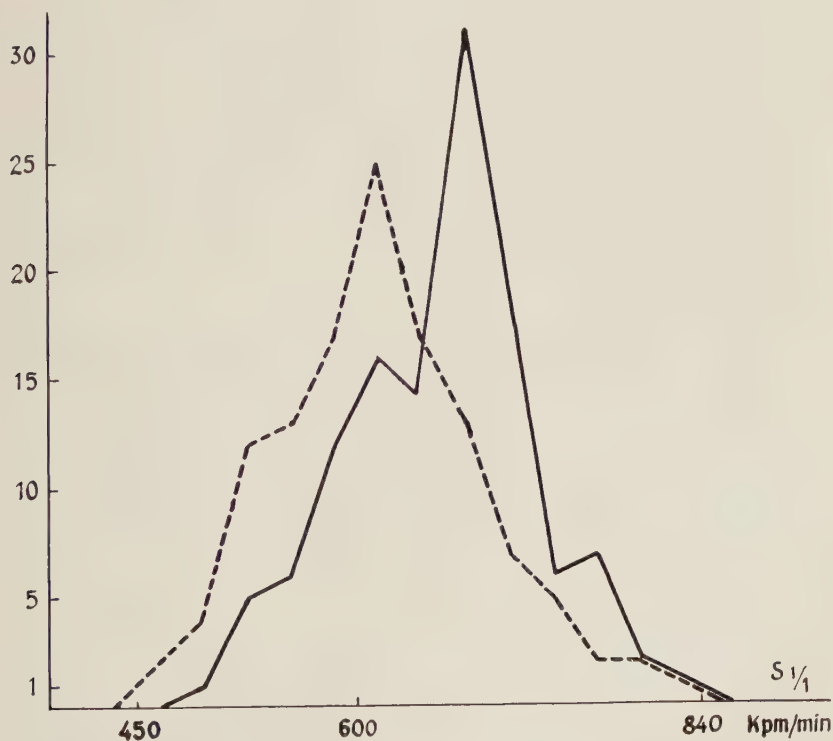


FIG. 4. Results of Experiment IV. Frequency distribution of reproduced stimulus values, $S_{1/1}$ ($S = 600$ kpm/min.). Broken line: Descending series. Whole line: Ascending series.

for the ascending values (M_a) is 658 ± 13 , for descending values (M_d) 615 ± 13 , and for all the values (M_{tot}) 636 ± 10 . As is to be seen M_a as well as M_{tot} lie above the standard value of 600 kpm/min. There is also a difference between M_a and M_d calculated on paired differences. There are, however, a few individual exceptions.

Table 3. Experiment II. Average of power level values (kpm/min) obtained in ascending (a) and descending (d) series at reproduction of 600 kpm/min. Number of Os = 12 with 10 values per O and series

O	Ascending	Descending	O	Ascending	Descending
1	669	585	8	690	585
2	656	624	9	634	545
3	703	698	10	554	590
4	616	631	11	685	594
5	655	602	12	728	634
6	661	695	Mean	658 ± 13	615 ± 13
7	640	600	Mean _{tot.}	636 ± 10	

Experiment III

In experiment I the time for the perception of the standard stimulus was kept constant. Thus the work was proportional to the power. It may, however, be of interest to illustrate how the amount of work influences the perception of the performance. This is easily done by allowing the O to perceive the standard power levels during varying periods of time. The purpose of this experiment was also to study the differences between the half-values carried out in ascending and descending scales.

Method

The experiment was carried out according to the ratio setting method with halving in both ascending and descending scales. Three standard power levels were used: — 400, 900, 1,500 kpm/min, and four different periods for the O to perceive the standards, 5, 10, 20, and 40 seconds. The time for halving was the same throughout, about 15 seconds. Twelve male students, 25 years of age, acted as Os. Between the separate as-

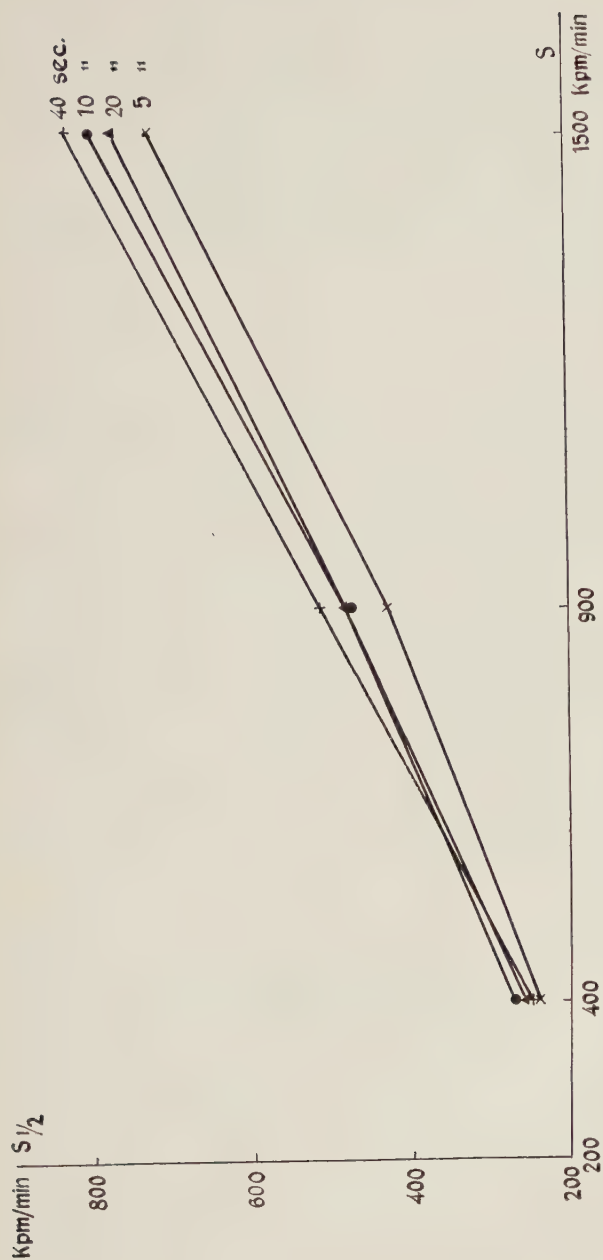


FIG. 5. Results of Experiment III. *Abscissa*: Stimulus values in power units. *Ordinate*: Half-values. Three power-levels, 400, 900 and 1500 kpm/min. connected by lines, and four different stimulus times, 5, 10, 20 and 40 secs.

assessments the *O*s were allowed to rest 30 seconds by alighting from the ergometer and stretching their legs.

Power levels and times were presented in a randomized order. At first 12 assessments were made (3 power levels $\times$ 4 periods of time) with every other assessment according to the ascending, *a*, and every other according to the descending, *d*, scale. Then the series was assessed backwards so that 24 assessments per *O* were obtained.

Results

The averages of the half-values for the 12 *O*s at different power levels and times are given in Table 4. In Figs. 5 and 6 a graphic description of the effect of the duration or the work is given.

Individual differences are seen to occur at the various tested durations; these differences will be illustrated in a subsequent experiment. The half-values are positively correlated for each duration as a result of these individual differences. The difference between the fixed half-values at separate times has been proved by tests on paired differences. At 400 kpm/min the average difference between 10 seconds ascending M_{10a} , and 5 seconds ascending M_{5a} , is significant at the 0.05 level. Moreover $M_{40a} - M_{40d}$ is significant at the 0.02 level, and the difference between ascending and descending values in the whole material, $M_a - M_d$, is significant at the 0.001 level. For the 900 power level $M_{40a} - M_{5a}$ is significant at the 0.01 level, and $M_{10a} - M_{5a}$ at the 0.05 level. For 1,500 finally $M_{40} - M_5$ is significant at the 0.05 level.

Table 4. Experiment III. Averages of half-values for 12 *O*s with 3 standard-powers: 400, 900 and 1,500 kpm/min with a duration of 5, 10, 20 and 40 seconds. Assessment in both ascending (*a*) and descending (*d*) series

Time	Power			Time	Power		
	400	900	1,500		400	900	1,500
5 <i>a</i>	246	387	759	20 <i>a</i>	289	445	787
5 <i>d</i>	230	471	716	20 <i>d</i>	237	513	760
10 <i>a</i>	319	471	797	40 <i>a</i>	286	523	871
10 <i>d</i>	223	486	800	40 <i>d</i>	212	507	786

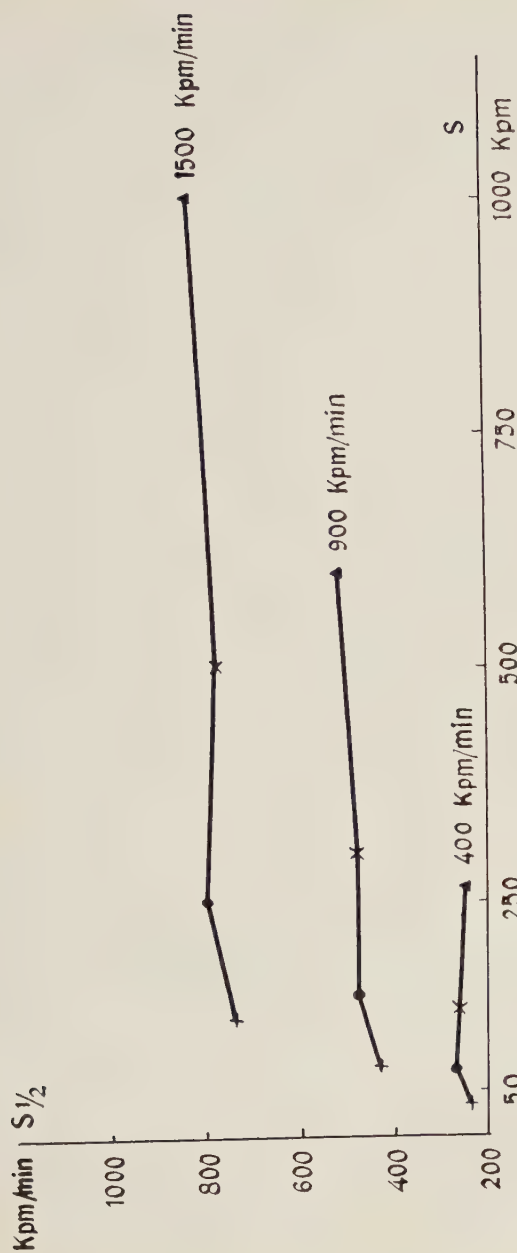


FIG. 6. Results of Experiment III. *Abscissa*: Stimulus values in work units. *Ordinate*: Half-values (power units) — Stimulus time symbols: + 5 secs, • 10 secs, × 20 secs, ▲ 40 secs.

Experiment IV

This experiment is a direct continuation of the previous one. Our intention was to make a more detailed study of the importance of the duration of work for times up to 100 seconds. Other problems of interest concerned the differences between *O*s and development tendencies *i. e.* possible training and fatigue effects during the experiment.

Method

The same bicycle ergometer was used as in previous experiments, with certain improvements. To decrease the excessive initial resistance, which the ergometer offers before the required velocity is attained, the ergometer was supplied with a push button control for the momentous release of the brake-resistance. This control could be operated by the *O* and the setting of the adjuster was not thereby changed.

Two series of experiments were carried out according to the ratio setting method with halving, one with the standard power 600 kpm/min, the other with 800. Four different periods of time were used *viz.* 5, 30, 60, and 100 seconds which were presented to the *O*s at random according to a 4×4 Latin Square. For each *O* eight assessments were made, half in ascending and half in descending series *i. e.* a total of 32 assessments per *O*. Twenty-one nurses and female students whose ages ranged from 20 to 35 years acted as *O*s, 11 at 600 and 10 at 800 kpm/min.

Results

The averages of the half-values for periods of time and for *O*s are given in Table 5. A three-way analysis of variance was made of the assessments in ascending and descending series. The values cover periods of time (*t*), *O*s (*i*), and development (*u*). In order to study the latter factor the material was divided into four parts with the four first values (*M* of $a + d$) in the first fourth part, the next four in the second and so on. The result of the analysis of variance is given in Table 6. On the

600 level the *F*-ratio for times, $\frac{s_t^2}{s_{ii}^2}$, is significant at the 0.05 level, and the interaction between *O* and development $\frac{s_{iu}^2}{s_{iiu}^2}$ at the 0.01 level.

According to McNEMAR (1957) no test of the significance of individual differences is possible by this mixed model, because no suitable interaction variance could be used when forming the F -ratio. However, we have ventured to test s_i^2 against the following combination of interaction variances: $s_{ii}^2 + s_{iu}^2 - s_{iui}^2$. In this way the numerator of the F -ratio only differ by one term involving the effect to be tested.

When interpreting the F -ratio the question of the number of degrees of freedom for the combination of variances arises. One possibility is to follow the rules presented by COCHRAN (1951), although these rules and this method for testing the reliability are open to doubt. The problem concerning the components that cause the variance within the O s appears to be a topic of discussion among mathematical statisticians at present. Some consider that the three interaction terms should not be included, while others are of a contrary opinion (McNEMAR, personal communication). In our case the F -ratio is of the order of size that the differences between the O s are considered amply established. ($F = 8$. With $df = 30$, the 0.01 level is at $F = 3$.)

A reliability coefficient was assessed in agreement with Hoyt's formula (GUILFORD, 1954), $r_u = 1 - \frac{s_{iui}^2}{s_i^2}$, whereby the three-way term was considered to estimate error of measurement variance. A very high coefficient was obtained *viz.* 0.95.

At the 800 power level the F -ratio for times, as also at 600, is significant at 0.05 level, the interaction between individuals and development is highly significant, as well as the interaction between time and individuals. The reliability was still higher than on the previous power level with $r_u = 0.98$.

In Fig. 7 the half-values for different durations are plotted against the power, and in Fig. 8 all half-values against the work performed. The curve for the 800-level agrees rather well with the one for the 600 level.

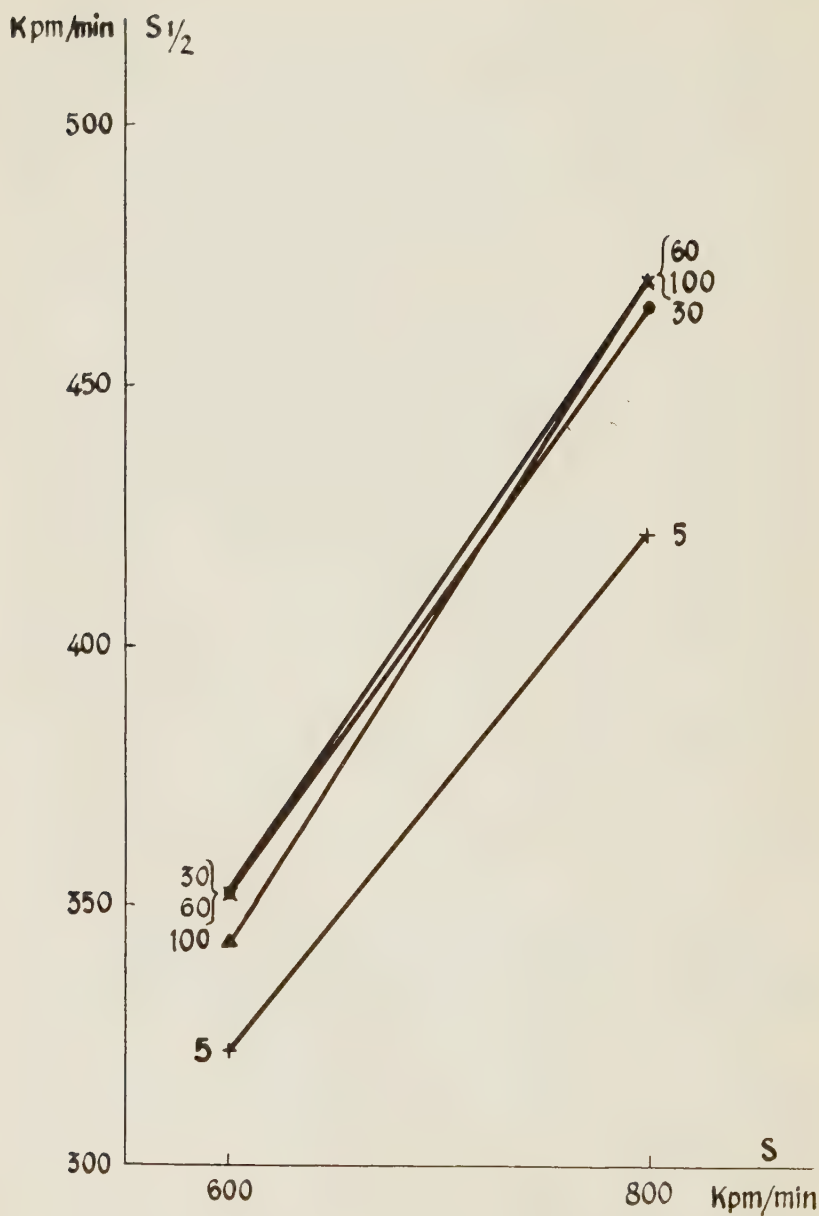


FIG. 7. Results of Experiment IV. *Abcissa*: Stimulus values in power units. *Ordinate*: Half-values, Two power-levels, 600 and 800 kpm/min., connected by lines and four different stimulus times, 5, 30, 60 and 100 secs.

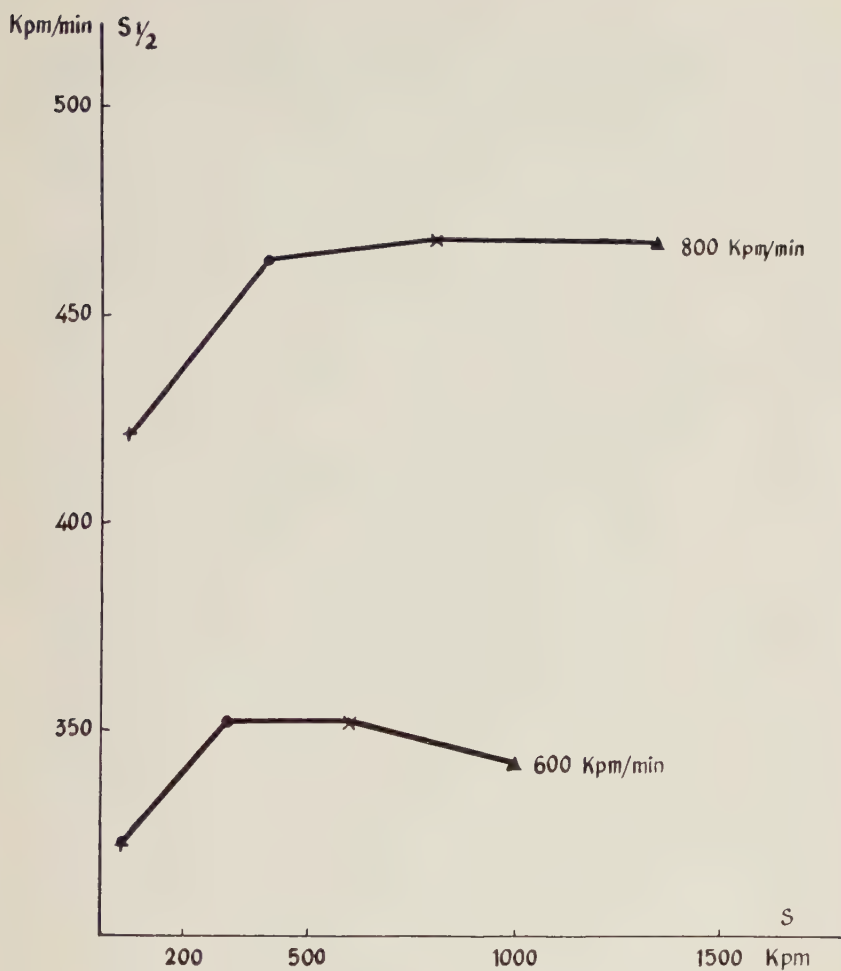


FIG. 8. Results of Experiment IV. *Abscissa*: Stimulus values in work units. *Ordinate*: Half-values (power units). — Stimulus time symbols: + secs., ● 30 secs, × 60 secs and ▲ 100 secs.

Table 5. Experiment IV. Half-values for work during 5, 30, 60 and 100 seconds. The values represent the averages of 8 assessments per time and O, of which half were obtained in ascending and half in descending series

	O	5 sec.	30 sec.	60 sec.	100 sec.	Mean
600 kpm/min	1	342	466	408	434	413
	2	325	301	322	306	313
	3	273	330	333	278	303
	4	224	209	278	228	235
	5	338	394	341	353	356
	6	290	357	347	348	336
	7	311	305	316	287	305
	8	402	361	425	372	390
	9	309	333	313	316	318
	10	333	336	368	373	352
	11	395	479	425	468	442
	Mean	322	352	352	342	342
800 kpm/min	1	326	404	369	392	373
	2	331	516	459	421	432
	3	352	387	382	347	367
	4	417	345	520	523	451
	5	350	334	355	368	352
	6	455	512	497	502	491
	7	439	522	461	542	491
	8	473	543	557	552	531
	9	687	675	716	683	690
	10	378	405	379	358	380
	Mean	421	464	469	469	456

Table 6. Experiment IV. Three-way analysis of variance of half-values (*M* of *a* + *d*) with *F*-ratios

600 kpm/min

Source	Sum of Squares	<i>df</i>	Variance Estimate
Time, <i>t</i>	26,688	3	8,896
Individuals, <i>i</i>	534,869	10	53,487
Development, <i>u</i>	34,559	3	11,520
Interaction, <i>ti</i>	87,495	30	2,917
» , <i>tu</i>	35,778	9	3,975
» , <i>iu</i>	185,590	30	6,186
» , <i>tiu</i>	221,180	90	2,458
Total	1,126,159	175	

$F_t = 3.05$ (0.05 level at 2.92); $F_u = 1.86$; $F_i = 8.05$ (0.01 level at 2.98, $df = 30$);
 $F_{iu} = 2.51$ (0.01 level at 1.98); $F_{tu} = 1.62$

800 kpm/min.

Source	Sum of Squares	<i>df</i>	Variance Estimate
Time, <i>t</i>	66,050	3	22,017
Individuals, <i>i</i>	1,522,433	9	169,159
Development, <i>u</i>	39,539	3	13,180
Interaction, <i>ti</i>	172,270	27	6,380
» , <i>tu</i>	12,095	9	1,344
» , <i>iu</i>	712,410	27	26,386
» , <i>tiu</i>	195,175	81	2,410
Total	2,719,972	159	

$F_t = 3.45$ (0.05 level at 2.96); $F_{ti} = 2.65$ (0.001 level); $F_{iu} = 10.9$

Experiment V

The problem deals with the more detailed construction of a psychophysical scale for subjective power, perceived during work of short duration. In Experiment I the set values of the individuals were plotted against the perceived powers. However, by this method a time-order error is obtained as seen by Experiment II. In order to reduce this error reproduction of the standard power was also carried out so as to enable

the plotting of the ratio setting values against those reproduced (EKMAN & FRANKENHAEUSER, 1957).

As in Experiment I the ratio setting method, halving the stimuli, was used. Five standard power-stimuli, 500, 700, 900, 1,100, and 1,300 kpm/min, were presented at random to the *O* with both a halving and reproducing of the stimuli in ascending and descending series. The same stimuli were then presented to the *O*s in a reversed order so that the total $5 \times 2 \times 2 \times 2 = 40$ assessments were obtained per subject.

Twelve healthy male students, about twenty-five years of age, volunteered as *O*s. The first 6 (Group A) were retested about one month later.

When the *O* had become accustomed to the work on the ergometer and experienced the whole scale of power, he was instructed to perceive as accurately as possible how strenuous the pedalling was (the degree of pedal resistance), and then to adjust the power so that the strenuousness of the ergometer seemed to have been reduced by one half (half the pedal resistance). He was also instructed to adjust the power to the initial level (to reproduce the same pedal resistance) when it had been increased or decreased by the technician. A preexperimental training series was carried out at 900 kpm/min.

A period of 30 seconds was considered suitable for the *O* to work and perceive the standard power. The *O* was then given about 15 seconds for halving. Between every assessment he was allowed to rest about 20 seconds by stepping off the cycle and walking a few yards. Half way through the experiment he was allowed a further ten minutes' rest. The whole experiment took about an hour.

Results

In Table 7 are to be seen the half-values, $S_{1/2}$, and the reproduction values, $S_{1/1}$, for the 5 standard power-stimuli. The values consist of the means of 4 determinations, 2 ascending and 2 descending series. The retest values for half of the *O*s, Group A, are also included in Table 7.

A three-way analysis of variance with the sources power (*p*), occasion (*o*), and *O*s (*i*) was made on the half-values of Group A. The result of the analysis is seen in Table 8. The *F*-ratio for *O*s has, as in Experiment IV, been tested with a combination of interaction variances in the denominator:

$$F_i = \frac{s_i^2}{s_{oi}^2 + s_{pi}^2 - s_{poi}^2} = 10. \text{ It will be seen that the } F\text{-ratio is of that}$$

magnitude that the individual differences must be considered very reliable. The F -ratio for occasions was not significant, but for the interaction between occasions and O_s was significant at the 0.05 level.

A coefficient of reliability was also assessed according to the formula

$$r_{tt} = 1 - \frac{s_{poi}^2}{s_i^2}. \text{ A very high coefficient was obtained viz. } 0.96.$$

Table 7. Experiment V. Half-values, $S_{1/2}$, and reproduction values, $S_{1/1}$ for 5 standard power-stimuli. The values consist of the means of 4 determinations, 2 ascending and 2 descending series. For half of the 12 O_s , Group A, the retest values are also included (A_{II}). The values are expressed in units of power (kpm/min)

		500		700		900		1,100		1,300	
		$S_{1/2}$	$S_{1/1}$	$S_{1/2}$	$S_{1/1}$	$S_{1/2}$	$S_{1/1}$	$S_{1/2}$	$S_{1/1}$	$S_{1/2}$	$S_{1/1}$
Group A _I	1	331	538	520	728	635	928	788	1,104	957	1,321
	2	288	473	335	732	566	899	685	1,172	870	1,302
	3	328	605	455	759	631	1,063	720	1,233	896	1,433
	4	219	452	332	619	358	829	481	1,059	706	1,176
	5	251	458	383	691	527	904	553	1,092	816	1,298
	6	208	481	274	695	441	939	579	1,163	688	1,302
	M	271	501	383	704	526	927	634	1,137	822	1,305
Group A _{II}	1	314	468	469	688	703	918	842	1,160	894	1,294
	2	215	454	336	680	405	897	542	1,098	689	1,317
	3	255	516	482	682	517	868	661	1,045	891	1,191
	4	225	509	312	632	424	851	559	1,014	669	1,282
	5	270	431	369	627	472	871	580	999	634	1,142
	6	223	477	310	651	471	896	532	1,046	807	1,286
	M	250	476	380	660	499	884	619	1,060	764	1,252
Group B	1	283	483	419	670	523	906	702	1,114	792	1,250
	2	261	473	385	702	510	853	577	1,020	746	1,167
	3	239	508	371	722	417	956	595	1,148	660	1,249
	4	312	515	438	757	485	925	622	1,054	801	1,304
	5	260	591	427	667	510	897	627	1,038	805	1,360
	6	238	511	361	675	486	948	535	1,098	715	1,365
	M	266	514	400	699	489	914	610	1,079	753	1,283
M _{tot}		262	497	388	688	505	908	621	1,092	780	1,280

Table 8. Experiment V. Three-way analysis of variance of the half-values, $S_{1/2}$, for Group A, with F-ratios

Source	Sum of Squares	df	Variance Estimate
Power, p	2,068,987	4	517,247
Occasion, o	9,350	1	9,350
Individuals, i	343,230	5	68,646
Interaction, po	5,069	4	1,267
» , pi	46,766	20	2,338
» , oi	34,108	5	6,822
» , poi	46,418	20	2,321
Total	2,553,928	59	

$F_p = 220$; $F_o = 1.37$; $F_i = 10$ $F_{oi} = 2.94$; $F_{pi} = 1.00$

An R - S -function was assessed for the means of the values of the O s. By the method of least squares a straight line was at first adjusted to the plot of half values against the reproduction values whereby the following equation was obtained: $S_{1/2} = 0.643 S_{1/1} - 62.90$. In the general

expression $R = c(S + a)^n$, $a = \frac{-62.90}{0.643 - 1} = 176$ and $n = \frac{\log 0.5}{\log 0.643} = 1.6$.

The following power function was thus obtained: $R = c(S + 176)^{1.6}$. It may be described by a curve of the same shape as the one in Fig. 3.

Discussion

Our results show that psychophysical ratio-scaling methods can be used to scale the perception of muscular force or work. Thus individual R - S -scales may be constructed.

In the majority of psychophysical experiments with ratio-scaling, where the variable stimulus must be presented after the standard, a so-called time-order error is obtained so that the O when reproducing the standard sets a lower (or sometimes a higher) value than the standard value in agreement with a common memory effect.

In our first scaling experiment the half-values were plotted against the standard values. To what extent the time-order error effected the results we know not. Experiment II with reproduction of 600 kpm/min

gave us some idea of this error. A positive error was obtained which may be difficult to explain. But the result applies only to one power level and duration. It is possible that a tendency towards central dominance in halving resulted in a positive direction as 600 kpm/min in these short-time experiments for most individuals is a rather low level.

In Experiment V both positive and negative time-order errors were obtained in the first series. But in the retest values negative errors were predominating. There seems to be rather great individual differences.

In the introduction it was pointed out that the connection which exists between the physical parameters work, power, time, and the speed of movement for the perception of muscular performance is unknown. The aim of Experiments III and IV was to study how the amount of work influences the perception. The harmony of the two experimental series is remarkably good. With short time work the *O* sets lower half-values when the standard has been perceived during 5 seconds than when it has been perceived 30 to 100 seconds. The perceived performance thus appears not only to depend upon the physical power or the force, but also on the amount of work carried out. This increases linearly with the time, as the power is constant, but seems to influence the perception of the performance (pedal resistance) during the first 10 to 20 seconds so that the resistance is perceived to be less in a shorter than in a longer period of work.

The great variation in the results of different experiments concerning weight perception may, in our opinion, be explained partly by the results of our experiments with the variation of time. The physical units behind the weight perception are the same as for work on the ergometer. It would appear, however, that in weight experiments appropriate consideration has often not been paid to the time or speed with which this muscular performance is carried out. The force has thus often been permitted to vary without the power or the work being kept under control. Our experiments show that the amount of energy plays an important part for the perception, particularly for periods of short duration.

The *R-S*-function arrived at in Experiment V, $R = c(S + 176)^{1.6}$ is in good agreement with the one obtained in Experiment I by a partly different method. In agreement with physiological practice the *S*-values are expressed in units of power. As the pedalling velocity and the time were kept constant units of force or work could just as well have been used.

The positive a -value of 176 units of the power function should be interpreted in such a manner that the individual perceives a primary "perceptual noise" and a force depending upon the pedalling without brake resistance. The exponent 1.6 is of the magnitude to be expected in comparison *inter alia* with experiments in the field of perception of weight.

Differences between the O s have been obtained in all the series of experiments. These differences are seen in the exponents and constants of the R - S -function, the size of the time-order error, the effect of duration and probably the dispersion. The interaction effect between individuals and development in Experiment IV may, for example, be an expression of the differences in physical fitness of the O s.

In the field of clinical diagnostics experiments of the type described here should be of value for differential psychological studies. In connection with current physiological tests of work capacity, where muscular work of longer duration are applied, similar studies appear to be fruitful. Such experiments are in progress.

It should be of great theoretical interest to venture to explain the psychophysical functions by means of parallel studies of physiological parameters. This might also facilitate interindividual comparisons.

Summary

This study deals with the psychophysical problem of the perception of muscular work. With the aid of the ratio setting method the perception of work on the bicycle ergometer has been studied. It has thus been possible to measure the intensity of the perception of power. This proved not only to be dependent upon the standard power levels but also upon the duration of the standard power *i. e.* the amount of work carried out. The effect of the so-called time-order error has been illustrated and in one scaling experiment been reduced by plotting the ratio setting values against those reproduced. Thus individual R - S -scales may be constructed. The following power function for the mean values was obtained: $R = c(S + 176)^{1.6}$ where S is measured in kpm/min.

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